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SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-TP-2000-173**
B. Chehroudi (ERC); R. Cohn, D. Talley (AFRL/PRSA) "The Behavior of Cryogenic Shear Layers under Supercritical Conditions"

2nd International Symposium on Turbulence and Shear Flow Phenomena (Statement A)
(Stockholm, Sweden, 27 Jun 2001) (Submission Deadline: 11 Sep 00)

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The Behavior of Cryogenic Shear Layers under Supercritical Conditions

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As combustion chamber pressures increase in order to realize higher performance and efficiency in a wide range of propulsion applications, the injected fluid may experience ambient pressures which exceed the critical pressure of the injected propellants. For example, in the cryogenic liquid hydrogen/liquid oxygen Space Shuttle main engine, the thrust chamber pressure is more than 4 times larger then the critical pressure of oxygen. In these applications, the initial temperature of the injected oxygen can initially be below the critical temperature, and then undergo a transition to a supercritical temperature as the oxygen is mixed and burned in the combustion chamber.

At these elevated chamber conditions, in which propellants are now being injected, the propellants experience a supercritical state. This results in many new issues which must be better understood in order to advance engine design and performance predictability. In single component fluids, the distinct difference between the gas and liquid phase disappears. Surface tension and enthalpy of vaporization vanish, and large variations in the density, thermal conductivity, and mass diffusivity occur near the critical point. For multi-component fluids, the solubility of the gas phase in the liquid phase increases as the pressure approaches the critical pressure and mixture effects need to be taken into account in calculating the critical properties. Understanding the effect of these differences on the shear layer of the injected propellant is vital to understanding the mixing and performance characteristics of these high performance engines. Until recently, our understanding of the injection process under these conditions has been limited. However, recent work in both experimental and theoretical areas has begun to allow a picture of the cryogenic supercritical shear layer to emerge.

Initial experimental efforts have made use of flow visualization to examine the formation and evolution of the jet and the differences within the shear layer between the injectant and ambient conditions. Using flow visualization, Newman and Brzustowski (1971), Mayer *et al.* (1998), and Woodward and Talley (1996), and Chehroudi, *et al.* (1999) have reported a gas jet-like visual appearance at a supercritical chamber temperature and pressure. Complimentary to these flow visualization results, more quantitative information has been acquired using spontaneous Raman scattering by Woodward and Talley (1996), Decker *et al.*(1998), Oschwald and Schik (1999), and Chehroudi *et al.* (2000). In this paper, we will describe efforts to use visualization information as well as density information to gain quantitative information about the supercritical shear layer.

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For the present paper, experiments were conducted in the high-pressure injection facility located at AFRL. This facility is capable of withstanding pressures up to 137 atm and temperatures ranging from cryogenic to 473 K. Visualization of the jet is through two facing sapphire windows. Access for laser diagnostics is provided through two slot-shaped quartz windows perpendicular to the sapphire windows. The working section can be pressurized with nitrogen, or other gasses as required. A liquid nitrogen jet is injected into the pressurized section containing either nitrogen or helium gas through a sharp-edged stainless steel tube approximately 50 mm long and with an inner diameter of 508 um. This size injector ensures a fully-developed turbulent pipe flow at the exit plane.

Over the past several years of study at AFRL, an integrated picture of the behavior of this cryogenic flow has begun to emerge. Visualization results for nitrogen into nitrogen injection shown in Figure 1 indicates that at low, subcritical, chamber pressures, the jet appears liquid-like with instabilities that grow downstream of the injector. In the shear region, very fine drops were ejected from the jet. Major structural changes occur near the critical pressure. Above $P_r = 1$, drops are no longer detected in the shear region. These drops are replaced by small comb-like ligaments which "dissolve" into the surrounding media due to combined effects of the reduction in surface tension and negligible latent heat of vaporization. As chamber pressure is increased further, the jet begins to take on the appearance of a turbulent gas jet injected into gaseous conditions.

Further examination of the shear layer of this supercritical, cryogenic jet has revealed additional properties that are similar to those of the shear layer of a turbulent gas. A fractal analysis of the shear layer interface clearly indicate a transition from a Euclidean to a fractal interface, with a fractal dimension close to values measured for gaseous turbulent shear layers. An examination of the shear layer growth rate, using both visualization and Raman scattering data, also indicates that the growth rate of the supercritical cryogenic jet is consistent with that of shear layer surrounding gas jets. Figure 2 shows a plot of the tangent of the spreading angle (i.e. growth rate) as a function of the chamber-to-injectant density ratio for both sub- and super-critical cryogenic results from the present study along with those of other researchers. Note that the results presented represents the sub- and super- critical jets of the current study as well as turbulent jets and sprays. Near and supercritical pressures, the cryogenic results agree well with the theoretical growth rate equations proposed by Brown (1974), Papamoschou and Roshko (1988), and Dimotakis (1986) for incompressible variable-density gaseous shear layer. Based on this data, an equation was developed proposing that the at the point of transition from liquid-like to gas-like appearances, and growth rates, the characteristic time of the vaporization process is of the same order as that of the interfacial bulge formation/separation event. The model equation, which will be described in the paper, agrees well with the experimental growth rate data over a wide range of density ratio. Using Raman scattering, it is also possible to assess the self-similarity of the radial density profile in supercritical jets. In general, it is found that once suitable corrections are made for secondary reflections, the measured density is consistent with a self-similarity condition very similar to that of a turbulent gas jet. Using these corrected density values and a suitable equation of state, it is also possible to gain temperature profiles from the density information acquired using Raman scattering. This information will provide further insight into shear layer structure.

The studies to present provide a strong initial argument that many properties of shear layers at supercritical conditions can be treated as a variable-density gaseous shear layer. However, additional experimental, theoretical, and computational results are needed to find whether all properties of the supercritical shear layer agree with those of the turbulent gas shear layer.

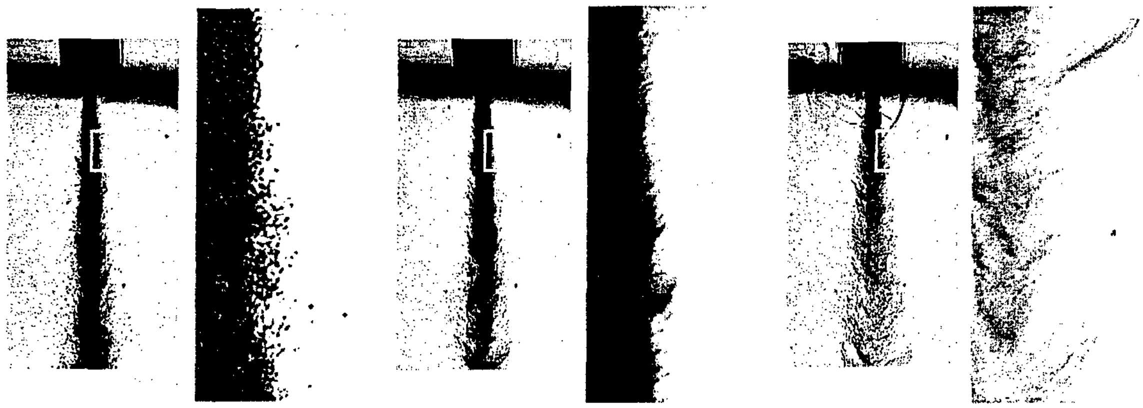

Figure 1. Liquid nitrogen injected into room temperature nitrogen at different pressures. The right-hand image of each set contains magnified images of the top row. The white box indicates the approximate location and the amount of magnification.

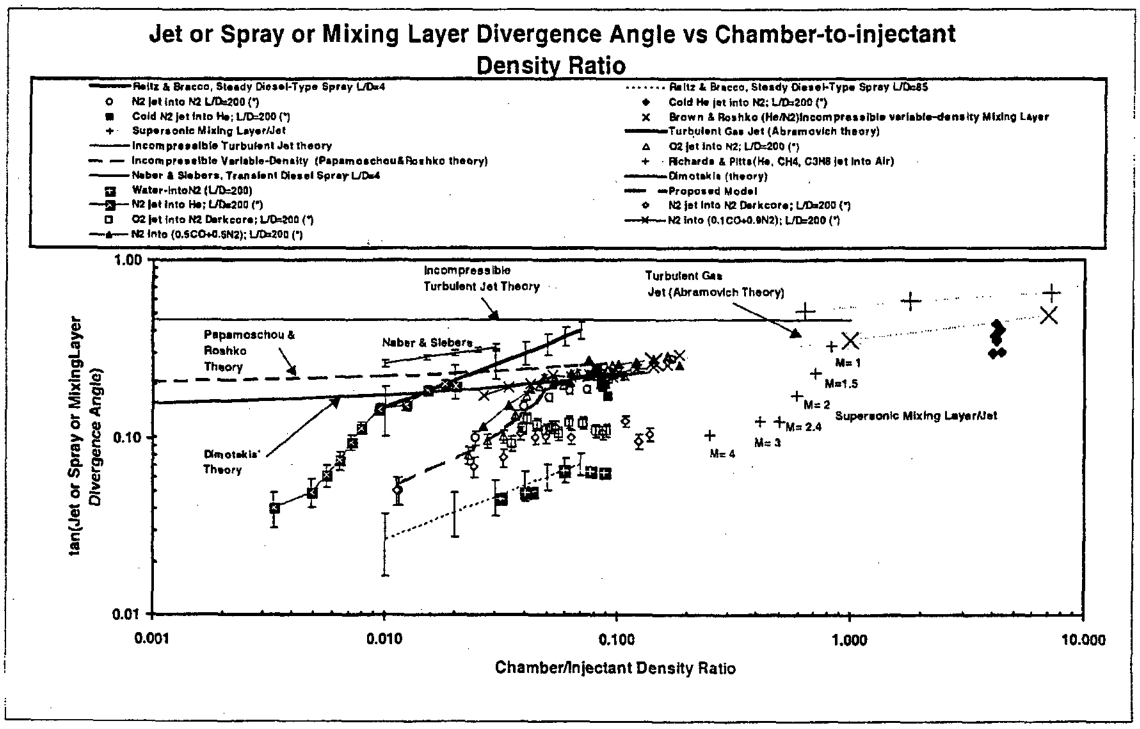

Figure 2. Tangent of the visual spreading angle versus the chamber-to-injectant density ratio. Data shown with an asterisk (*) was taken at AFRL.